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Horizontal Temperature Distribution in a Plus-energy House: Cooling Season Measurements

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ABSTRACT

The present study is concerned with the air and operative temperatures at different locations in a detached, one-story, single family, plus-energy house. The house was located in Denmark and it has been used as a full-scale experimental facility with heated dummies to simulate occupants living in the house. The house had gone through a year-round measurement campaign from October 2013 to October 2014, where various physical parameters were measured. This study focuses on the cooling season (May to September 2014, both months included). The house was cooled by means of floor cooling (a dry radiant system) and was ventilated with a mechanical ventilation system (heat recovery on ventilation). Inside the house, there was a single space combining kitchen, living room and bedroom areas. The thermal comfort of the occupant(s) in this space could differ based on the location of the occupant, and control of indoor environment in this single space could be challenging. The measurement of horizontal temperature distribution could address these issues and provide a means of improvement, if necessary. The measurements showed that a uniform thermal indoor environment was achieved inside the house. The average operative temperature difference between the reference point (in the occupied zone) and other measurement points was 0.2 °C (0.4 °F) and the highest temperature difference compared to the reference point was 1.6 °C (2.9 °F) during the measurement period . It was observed that a thermostat on the East Wall would follow the temperature changes in the occupied zone closely and, thus, would provide a good indication of the thermal indoor environment to the control system.

INTRODUCTION

This study focuses on the horizontal temperature distribution (air and operative temperatures at different locations) in a detached, one-story, single family house, located in Denmark (Kazanci et al. 2013), (Kazanci et al. 2014). The house had a single space interior and this single space was heated or cooled by a radiant floor (water-based radiant system). The house had gone through one year of operation where different heating and cooling strategies were tested (Kazanci and Olesen 2014). The results presented in this paper are from the cooling season (from May to September 2014, both months included).

Horizontal temperature distribution in museums (Camuffo et al. 1999), (Gysels et al. 2004), (Brimblecombe et al. 1999), in a large domed stadium (Nishioka et al. 2000), and in a room of an experimental house (Simone and Rode 2009) were previously studied.

Horizontal temperature distribution in a conditioned space could have significant effects on the occupant

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thermal comfort, depending on the location of the occupant(s), and on the control of the heating and cooling system (therefore on the energy consumption), depending on the sensor location and type (air or globe temperature), particularly in a house with a single space interior, as in the present case.

One of the advantages of radiant heating and cooling systems is providing a uniform temperature distribution in spaces (Olesen 2008), and this is important for achieving a satisfactory thermal indoor environment. Although radiant cooling helps to achieve this uniformity, operative temperature (which is influenced by the air- and mean radiant temperature) may vary due to other conditions such as warm or cold surfaces (e.g. windows). Warm or cold surfaces might also cause radiant temperature asymmetry, which could result in local thermal discomfort.

Previous studies have shown that it is more effective to use an operative temperature thermostat compared to an air temperature thermostat (Berglund and Berglund 1994), and a better temperature control can be obtained if a thermostat is placed in a central position in the space instead of on a wall (Madsen et al. 1990). Though, this might not be possible to realize in practice. Therefore, it is important to measure the temperature difference due to the sensor location evaluated by the horizontal temperature distribution.

In the present study, air and operative temperature measurements at different locations, during a cooling season were compared to evaluate the effects of horizontal temperature distribution on the occupant thermal comfort and on the control system.

DESCRIPTION OF THE HOUSE AND ITS HVAC SYSTEM

The studied house was a single family, detached, one-story house with a floor area of 66.2 m^2 (713 ft^2) and a conditioned volume of 213 m^3 (7521 ft^3). Interior of the house consisted of a single space combining kitchen, living room and bedroom. Shower and toilet were separated from the main indoor space by partitions. The technical room was completely isolated from the main indoor space, and had a separate entrance. The wall between the technical room and the indoor space was insulated with the same degree of insulation as the envelope.

The house was constructed from wooden elements. The walls, roof and floor structures were formed by installing prefabricated elements in a sequential order and sealing the joints. The North and South glazing façades were inserted later and the joints between the glazing frame and the house structure were sealed. The glazing façades in the North and South sides of the house were partly shaded by the overhangs. No solar shading was installed in the house except for the skylight window. The largest glazing façade was oriented to the North with a 19° turn towards the West. The exterior views of the house may be seen in Figure 1:

Figure 1 Exterior views of the house, seen from North-West (left) and South-West (right)

The surface areas and thermal properties of the structural elements of the house are given in Table 1:

Table 1. Thermal properties of the envelope

External walls	North	South	East	West	Floor	Ceiling
Area, m^2 (ft^2)	-	-	37.2 (400)	19.3 (208)	66.2 (713)	53 (571)
U-value, W/m^2K ($Btu/hft^2°F$)	-	-	0.09 (0.02)	0.09 (0.02)	0.09 (0.02)	0.09 (0.02)
Windows	**North**	**South**	**East**	**West**	**Floor**	**Ceiling**
Area, m^2 (ft^2)	36.7 (395)	21.8 (235)	-	-	-	0.74 (8)
U-value, W/m^2K ($Btu/hft^2°F$)	1.04 (0.18)	1.04 (0.18)	-	-	-	1.04 (0.18)
Solar transmission	0.3	0.3	-	-	-	0.3

The sensible cooling of the house relied on high temperature cooling via the hydronic radiant system. The floor cooling system was a dry radiant system, consisting of a piping grid installed in the wooden layer, with aluminum profiles on the pipes for better thermal conductance. The details of the floor system were: chipboard system, with aluminum heat conducting profiles (thickness was 0.3 mm [0.01 in.] and length was 0.17 m [0.6 ft]), PE-X pipe, 17x2.0 mm (0.7x0.08 in.). Pipe spacing was 0.2 m (0.7 ft). In total there were four loops in the floor. The available floor area for the embedded pipe system installation was 45 m^2 (484 ft^2).

The heat sink of the house for space cooling was air, realized by means of a reversible air-to-brine heat pump. There was a flat plate heat exchanger between the hydronic radiant system and the air-to-brine heat pump. The part between the heat exchanger and the heat pump was filled with an anti-freeze mixture (40% ethylene glycol).

A mixing station (and a controller), that links the radiant system with the heat sink, was installed to control the flow to each loop, and the supply temperature to the radiant system. The operation of the radiant system was based on the operative temperature set-point that was adjusted in a room thermostat (a matt gray half-sphere) with 0.5 °C (0.9 °F) intervals and on the relative humidity inside the house (to avoid condensation).

The mechanical ventilation was only used to provide fresh air into the house since the main sensible heating and cooling terminal of the house was the radiant system. Fresh air was provided into the house by an air handling unit, AHU, which had passive and active heat recovery possibilities. The passive heat recovery was obtained by means of a cross-flow heat exchanger and it had an efficiency of 85% (sensible heat). The AHU could supply fresh air at a flow rate up to 320 m^3/h (188.4 cfm) at 100 Pa (0.4 in. w.c.). The design ventilation rate was 0.5 ach.

MATERIALS AND METHODS

Experimental Set-up

The house was used as a full-scale experimental facility from October 2013 to October 2014. There were no occupants living in the house but the occupants and equipment (internal heat gains) were simulated by means of heated dummies. A dummy is a circular aluminum duct, with a diameter of 0.22 m (0.7 ft) and a height of 1 m (3.3 ft). It had closed ends and an electrical heating element (wire) was installed on the internal surfaces of the duct. Dummies had an adjustable heat output up to 180 W (614 Btu/h), (Skrupskelis and Kazanci 2012).

The occupancy and equipment schedules were adjusted with timers. Two dummies were used to simulate occupants at 1.2 met (ON from 17 to 08 on weekdays and from 17 to 12 on weekends), one dummy (equipment #1, 120 W [410 Btu/h]) was always ON to simulate the house appliances that are always in operation, the fourth dummy (equipment #2, 180 W [614 Btu/h]) was used to simulate the house appliances which are in use only when the occupants are present and the fifth dummy was used to simulate the lights (180 W [614 Btu/h], ON from 06 to 08 and from 17 to 23 until 27/05/2014, and after this date, ON from 20 to 23 every day). The house also had ceiling mounted lights ON from 21 to 23 every day (140 W [478 Btu/h]). Additionally, there was a data logger and a computer (80 W [273 Btu/h]), and a fridge (30 W [102 Btu/h]) which were always ON.

At a certain point during the measurements, overheating proved to be a problem. To tackle this problem, internal solar shading (manually operated) was installed on the North façade, covering 20 m² (215 ft²), on 30/07/2014 and it was used in fully down position until the end of the experiments. The house was not cooled from 20/06/2014 to 23/06/2014 (the floor cooling and the AHU were OFF), due to a repair in the HVAC system.

Measurement Locations and Measuring Equipment

All the measurements presented are from 01/05/2014 to 01/10/2014, unless otherwise indicated. The abbreviations in the parentheses are used to indicate the measurement locations in Figure 2. Temperatures were measured at the following locations and heights:

1. Air temperature (on the technical room wall, at 1.52 m [5 ft] height) (**T**echnical **R**oom **W**all, TRW)
2. Air temperature (on the kitchen counter, at 0.92 m [3 ft] height) (**K**itchen **C**ounter, KC)
3. Air and operative temperatures (at the reference location, at 0.6 m [2 ft] height) (**R**eference, R)
4. Air and operative temperatures (1 m [3.3 ft] distance from the North façade, at 0.6 m [2 ft] height, from 31/07/2014) (**N**orth, N)
5. Air and operative temperatures (1 m [3.3 ft] distance from the South façade, at 0.6 m [2 ft] height, from 31/07/2014) (**S**outh, S)
6. Air and globe temperatures (on the East wall, at 1.7 m [5.6 ft] height, from 21/08/2014) (**E**ast **W**all, EW)

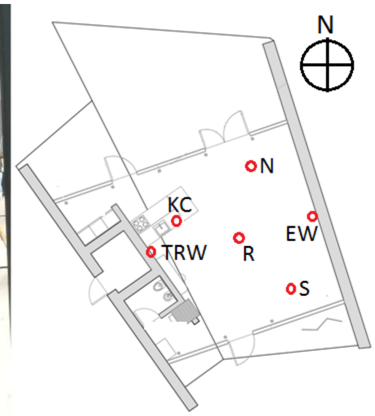

Figure 2 Panoramic view of the interior of the house (left) and the measurement locations on the plan drawing (right)

The measurement locations close to the North and South façades were chosen according to the occupied zone defined in (EN 13779 2007), and the reference point was a central location in the occupied zone.

The air temperature sensors used on the TRW and on the KC were enclosed in a plastic casing. For the rest of the measurements: the operative temperatures (see Appendix) were measured by a gray globe sensor, 4 cm (1.6 in.) in diameter. This sensor has the same relative influence of air- and mean radiant temperature as on a person, (Simone et al. 2007), and, thus, at 0.6 m (2 ft) and 1.1 m (3.6 ft) heights will represent the operative temperature of a sedentary or a standing person, respectively. The air temperature sensor was shielded by a metal cylinder to avoid heat exchange by radiation, (Simone et al. 2013). The output from the sensors was logged via a portable data logger.

EXPERIMENTAL SETTINGS

During the cooling season, the house was cooled by floor cooling and was ventilated with the mechanical ventilation system (heat recovery on ventilation). Different operative temperature set-points (to control the operation of the radiant system) and different ventilation rates were implemented. The most important boundary conditions regarding different cases in cooling season are given in Table 2 (HV: higher ventilation rate, S: solar shading):

Table 2. Periods and experimental settings of the case studies

Period	Average external air temperature, °C (°F)	Floor cooling set-point, °C (°F)	Ventilation type and ventilation rate	Solar shading	Case study abbreviation
1st of May to 27th of May*	14.7 (58.5)	20 (68)**	Heat recovery, 0.5 ach	No	FH20
27th of May to 19th of June	18.7 (65.7)	25 (77)	Heat recovery, 0.5 ach	No	FC25
19th of June to 13th of July	18.7 (65.7)	25 (77)	Heat recovery, 0.8 ach	No	FC25-HV
13th of July to 30th of July	22.7 (72.9)	24 (75)	Heat recovery, 0.8 ach	No	FC24-HV
30th of July to 21st of Aug	18.1 (64.6)	24 (75)	Heat recovery, 0.8 ach	Yes	FC24-HV-S
21st of Aug to 1st of Oct	16.0 (60.8)	24 (75)	Heat recovery, 0.5 ach	Yes	FC24-S

*: The dummies simulating the occupants and the dummy, equipment #2, were OFF during this experimental period. **: Floor heating was active, transition period.

RESULTS AND DISCUSSION

The operative temperatures (at 0.6 m [2 ft] height) at three locations were used to evaluate the thermal comfort. The average temperatures, maximum and minimum temperature differences (ΔT) between the North and reference, and South and reference are presented in Table 3, together with the achieved indoor environment category according to (EN 15251 2007), based on the operative temperature. The operative temperatures at different locations from 31/07/2014 to 01/10/2014 are presented in Figure 3:

Table 3. The results of the measurements and thermal comfort evaluation

Location	Average temperature, FC24-HV-S, °C (°F)	Average temperature, FC24-S, °C (°F)	ΔT, FC24-HV-S, max/min, °C (°F)	ΔT, FC24-S, max/min, °C (°F)	Categories (1/2/3/4)*, FC24-HV-S	Categories (1/2/3/4)*, FC24-S
North	23.2 (73.8)	22.5 (72.5)	0.5 (0.9) / -1.1 (-2)	0.6 (1.1) / -1.0 (-1.8)	37% / 54% / 82% /18%	18% / 30% / 63%/37%
South	23.2 (73.8)	22.5 (72.5)	1.2 (2.2) / -0.6 (-1.1)	0.5 (0.9) / -1.6 (-2.9)	36% / 54% / 82% /18%	19% / 32% / 66%/34%
Reference	23.3 (73.9)	22.7 (72.9)	-	-	39% / 56% / 84% /16%	22% / 36% / 72%/28%

*: Category 1 is 23.5-25.5 °C (74.3-77.9 °F), Category 2 is 23.0-26.0 °C (73.4-78.8 °F), Category 3 is 22.0-27.0 °C (71.6-80.6 °F), Category 4 represents the values outside Categories 1, 2 and 3.

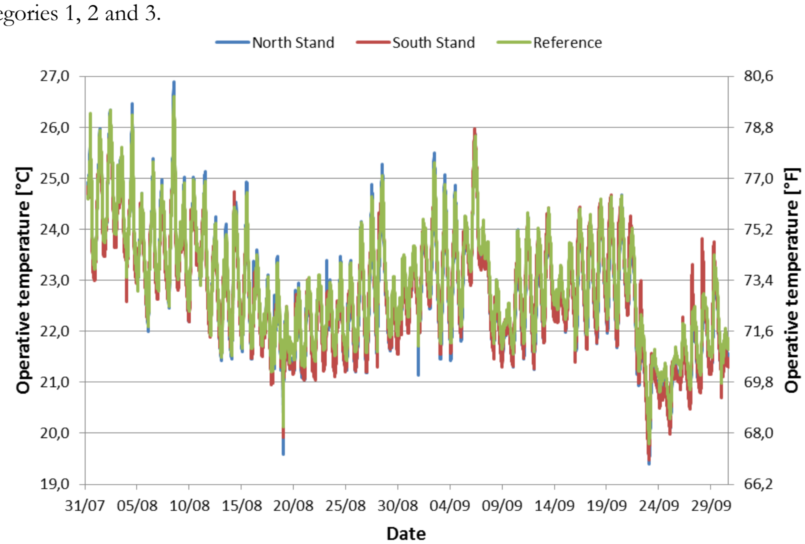

Figure 3 Operative temperatures at different locations from 31/07/2014 to 01/10/2014

The measurements showed that, the average operative temperature difference was 0.1 °C (0.2 °F) and 0.2 °C (0.4 °F) for different cooling strategies. The highest temperature difference compared to the reference point was 1.6 °C (2.9 °F). The achieved thermal indoor environment categories at different locations were very close, varying by only a few percent.

A uniform temperature distribution in the space was achieved during the measurement period; however a year-round evaluation of the temperature distribution is necessary for a final conclusion (the difference in the horizontal temperature distribution during winter should also be considered due to possible low window surface temperatures that could affect the mean radiant temperature, and create risk of draft). If the house didn't have large glass areas on both of its façades, then the radiant temperature asymmetry must have been considered.

It may be observed that the measurements from the North stand are closer to the reference, when compared to the South stand. This is because of the internal solar shading on the North façade. It is possible to observe that the measurements at the South stand were affected more than the North stand, by the window surface (i.e. lower temperatures in the nights and higher temperatures towards the end of the measurement period due to solar radiation on the sensors).

The average temperatures measured at different locations during the cooling season are presented in Table 4, the measured temperatures over the cooling season are presented in Figure 4, and the measured temperatures during a 10-day period in September 2014 are presented in Figure 5:

Table 4. Average temperatures obtained with different cooling strategies

Location, measured parameter	Average temperature, °C (°F)					
	FH20	FC25	FC25-HV	FC24-HV	FC24-HV-S	FC24-S
TRW, air	22.4 (72.3)	25.5 (78)	24.3 (75.7)	25.2 (77.4)	23.7 (74.7)	23.1 (73.6)
KC, air	22.9 (73.2)	26.1 (79)	25.0 (77)	25.9 (78.6)	24.3 (75.7)	23.5 (74.3)
EW, globe	-	-	-	-	-	22.5 (72.5)
EW, air	-	-	-	-	-	22.7 (72.9)
Reference, operative	22.2 (72)	25.1 (77.2)	24.0 (75.2)	24.8 (76.6)	23.3 (74)	22.7 (72.9)
Reference, air	22.1 (71.8)	25.1 (77.2)	23.9 (25)	24.8 (76.6)	23.3 (74)	22.6 (72.7)

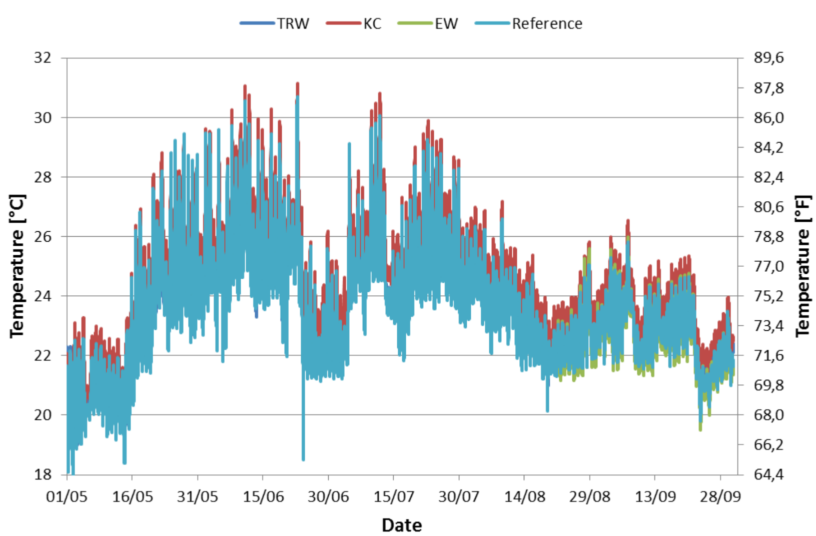

Figure 4 Measured temperatures during the cooling season by different sensors

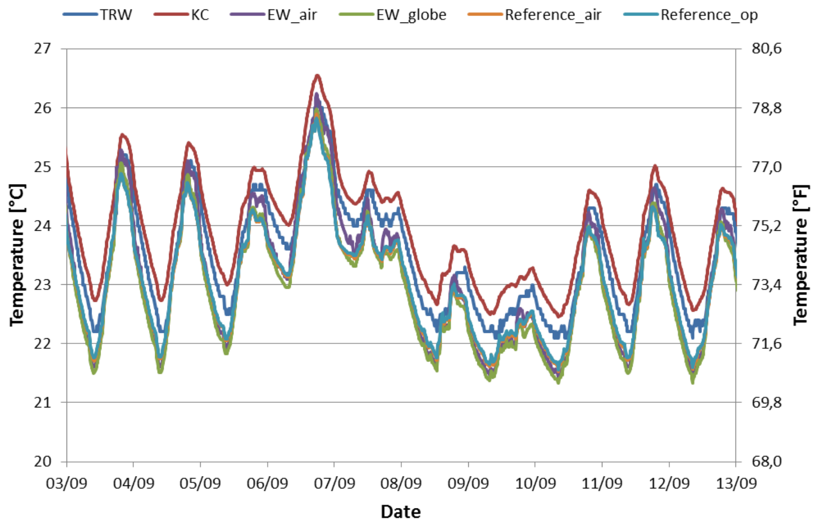

Figure 5 Measured temperatures during a 10-day period in September 2014

It may be seen from Table 4, Figure 4 and Figure 5 that, the measured temperatures on the KC and TRW were higher than the reference, throughout the measurement period. The measurements on the KC show the greatest difference compared to the reference. This behavior could be affected both by the locations of these sensors and due to the sensor types (i.e. in these locations, the air temperature sensors were located inside a small plastic casing, which might also affect the time constant). The measurements obtained from the East wall follow the measurements from the reference point closely, with slightly higher values during the warmest time of the day and with slightly lower values during the coldest time of the day.

CONCLUSION

Air and operative temperatures were measured during a cooling season at different locations in a single family house with a large single space interior. Measurements were used to evaluate the effects of horizontal temperature distribution on the occupant thermal comfort and on the control of the indoor terminal unit.

During the measurement period, a uniform horizontal temperature distribution was observed, mainly due to the radiant floor cooling, despite the large glass façades. The optimal position of the thermostat will be where the occupants are or where they are expected to be, and even though it was possible to place a thermostat in the occupied zone for experimental purposes, in practice this might not be possible and the only possible location of the sensors might be on the walls. For this particular house, placing the thermostat on the East wall would be a good approximation to placing it at the reference location, since it follows the temperature changes in the occupied zone closely. A definitive conclusion on this would require a longer measurement period.

ACKNOWLEDGMENTS

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APPENDIX

Operative temperature is defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment.